A CsI(Tl) Hodoscopic Calorimeter for the GLAST Mission

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Abstract – The Gamma-ray Large Area Space Telescope (GLAST) is a NASA mission concept under development by an international team for a possible new mission start in the year 2001. The instrument operates as an e^+e^- pair conversion telescope and supporting calorimeter imaging gamma rays in the 10 MeV to 300 GeV energy range. The baseline design consists of a modular array of e^+e^- pair trackers formed from multiple planes of Silicon strip detectors interleaved with converter foils of Pb. A matching array of calorimeters of CsI(Tl) are below the trackers. We present here the requirements and simulations of the performance of this imaging calorimeter.

I. Introduction

The Gamma Ray Large Area Space Telescope (GLAST) is a mission concept which is being studied for the Structure and Evolution of the Universe (SEU) discipline at NASA as the next space mission for high energy gamma ray observations in the 10 MeV to 300 GeV energy range. The GLAST concept (Fig. 1) is being developed by an international collaboration over 20 institutions under the leadership of Stanford University [1]. GLAST is intended to build on the discoveries of the Energetic Gamma-Ray Experiment Telescope (EGRET) on *NASA's Compton Gamma Ray Observatory* by providing an instrument which is 25 – 50 times more sensitive. The primary scientific targets for the GLAST mission include active galactic nuclei, gamma ray bursts, neutron stars and diffuse galactic and extragalactic high energy radiation. GLAST operates as an electron-positron pair conversion telescope in which an incident gamma-ray is identified by the detection of the e^- and e^+ that results from pair conversion in a thin lead converter. The measurement of the energy and direction of the e^-e^+ shower provides information about the energy and direction of the incident gamma ray. Table I summarizes the characteristics of the GLAST mission. The baseline GLAST design utilizes silicon strip detectors to track the direction of the electron and positron and includes a CsI(Tl) scintillation crystal calorimeter to measure the energy. (See Johnson et al. [2] for GLAST silicon detector information.) GLAST is designed as a modular system consisting of a 5 × 5 array of identical modules, called towers, with a base dimension of ~ 32 cm. Each tower contains elements of an anticoincidence system, the silicon tracker/converter and the calorimeter (see Fig. 2).

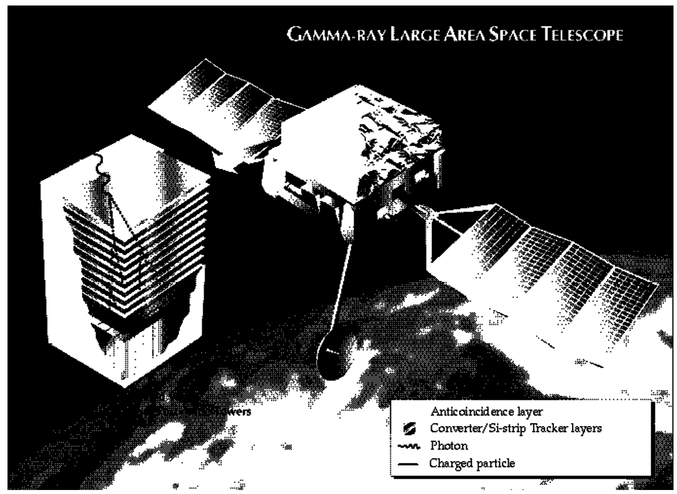

Fig. 1. The GLAST Mission Concept

TABLE I
THE CHARACTERISTICS OF THE GLAST MISSION

Characteristic	Requirement
Energy range	10 MeV – 300 GeV
Energy resolution (@ 1 GeV)	4.4%
Effective Area (@ 1 GeV)	8000 cm^2
Acceptance Solid Angle (FWHM)	$0.87 \times \pi$ sr
Single photon position error (@ 1GeV)	0.42°
Point source sensitivity	2×10^{-9} ph cm^{-2} s^{-1}
Volume	$1.75 \times 1.75 \times 0.8$ m^3
Mass	3000 kg
Power	600 W
Lifetime	> 5 yr

Several options for the calorimeter are under study by GLAST collaborators at NRL, NASA GSFC, Columbia Univ., Centre D'Etudes Saclay and Ecole Polytechnique in France, and Instituto Nazionale di Fisica in Italy. We present

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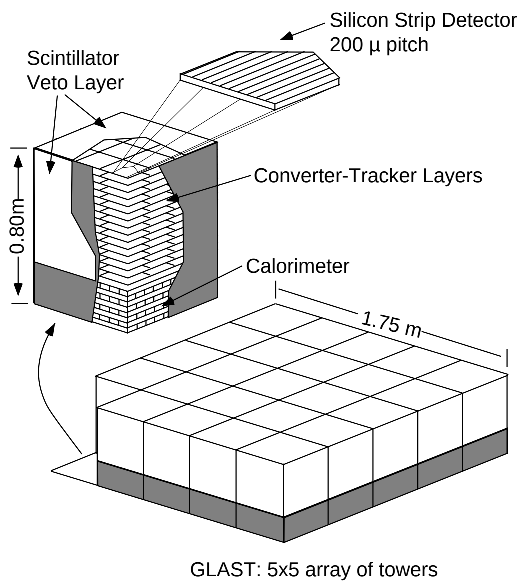

Fig. 2. Modular GLAST Design Concept

here the baseline calorimeter concept for GLAST which is a hodoscope of CsI(Tl) crystal blocks readout with PIN photodiodes.

II. CsI Calorimeter Requirements

The baseline modular GLAST calorimeter is constructed from CsI(Tl) scintillation blocks read out by PIN photodiodes. Each tower contains 80 blocks of approximate size 2.5 cm $\times$ 3 cm $\times$ 31 cm. The blocks are arranged horizontally in 8 layers of 10 blocks with alternate layers oriented with the long axis of the block perpendicular to that of the adjacent layers to form an x-y hodoscope. PIN photodiodes mounted on each end of the block measure the scintillation light seen at each end. The difference in the light levels at each end provides a determination of the position of the energy deposition along the CsI block. Thus, the layering and orthogonal positioning of events in the calorimeter provide the ability to reconstruct the electromagnetic shower in the calorimeter and, consequently, to determine the incident direction. In this mode, the calorimeter measurements alone can image the gamma-ray sky, albeit with less angular resolution than the silicon tracker above it. This imaging capability in the calorimeter is particularly interesting at high energies (>1 GeV) where the gamma-ray interaction probability in the silicon tracker is near 33%. The other 67% of the gammas will convert in the calorimeter and can be imaged there, thus increasing the effective area of GLAST by $\times$3 at high energies. This capability is particularly useful in spectroscopic studies of active galactic nuclei. The imaging capability is also important in cosmic ray background rejection where correlation of tracks in the silicon tracker with the position of energy deposition in the calorimeter provides improved discrimination against side-entering low energy trapped or cosmic ray protons. At high energies, the imaging calorimeter can discriminate between electromagnetic and hadronic showers.

Table II
Calorimeter Requirements Summary

Characteristic	Requirement
Number of Channels:	320 / tower
Dynamic Range:	3 x 10^5
Noise goal:	0.1 MeV (10^3 e^-)
A to D Range:	1 MeV – 40 GeV
Electronic Resolution:	~ 1% (except at threshold)
Trigger Rate: (GLAST)	400 Hz (orbit ave) 1600 Hz (peak) 20000 Hz (design max)
Self trigger delay:	< 1 μsec
Trigger Dead time:	50 μsec
Power:	5 watts / tower ~ 15 mW / channel

III. Prototype Calorimeter

The GLAST calorimeter is a modest endeavor when compared with calorimeters in the current accelerator-based high-energy physics experiments. At approximately 2500 kg and 10 radiation lengths (X_o) in depth, it would be the largest calorimeter launched into space. The design problem is to maximize the performance of GLAST within the weight and power budgets for a reasonable space mission. The challenges for the GLAST calorimeter are in 1) minimizing passive material which affects energy resolution, 2) minimizing the angular uncertainty in reconstructed track direction (leading to more sampling of the shower), 3) minimizing the electronics power per channel, and 4) covering the broad dynamic range of energy losses in a single CsI block of approximately $3 \times 10^{5.}$ The large dynamic range will be achieved by using 4 photodiodes on each block – two on each end attached to preamps with differing gain.

A. Mechanical Design

The modular nature of the calorimeter (segmented into 25 tower elements) and the structural material required to support the calorimeter through launch loads conspire to provide "leakage paths" in the GLAST calorimetry where particle energy escapes the calorimeter through the cracks or gaps in the CsI between tower modules. This leakage can adversely affect the spectral resolution of the calorimeter. A major task in the mechanical design of the calorimeter is minimizing these "dead" or inactive areas in the calorimeter while safely providing structural support for launch loads. This problem is exacerbated by the large coefficient of thermal expansion of CsI relative to those of potential structural materials.

The materials used should all have a very low atomic number to interact minimally with the electromagnetic showers. Yet the mechanical structure for each module has to support ~ 100 kg of CsI with a launch load of ~ 10 g. The material of choice is therefore carbon fiber composite. The basic mechanical concept is a carbon fiber composite box (see Fig. 3).

The individual CsI crystals detectors will be stacked in the carbon fiber composite box. The crystals will push against each other and ultimately against the walls of the box. Since the crystals are somewhat brittle and have a very large coefficient of thermal expansion, a layer of elastomeric padding is inserted between the carbon fiber composite and the outer crystals. The pad will be compressed upon assembly of the module to provide the loading against launch vibrations and allow for thermal expansion. The sides of the mechanical support will consist of four corner posts connecting the top and bottom plates and individual "compression bars" to hold the crystals in place. This relatively hollow geometry is required because room must be allowed for the PIN diodes reading out the crystals.

The front end electronics to read out the PIN diodes is also to be located near the diodes and crystals. A small electronics board containing the front end electronics for a vertical stack of crystals will therefore be inserted between each set of compression bars. This circuit board will also be the path for the signals and channel them to the bottom of the calorimeter, where each circuit card will connect to the calorimeter digital electronics located in an electronics box below the calorimeter. The crystal, and hence the PIN diode, will expand and move up to 1 mm under thermal expansion, whereas the carbon fiber and circuit card will be unchanged. The leads connecting the PIN to the circuit board will compensate for this differential expansion.

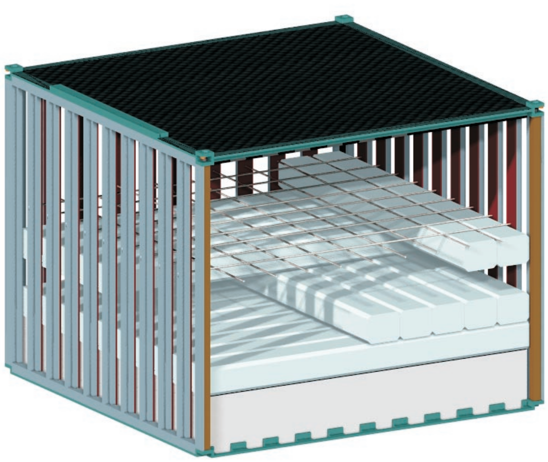

Fig. 3. Calorimeter compression cell design. For clarity, one panel of compression bars is not shown.

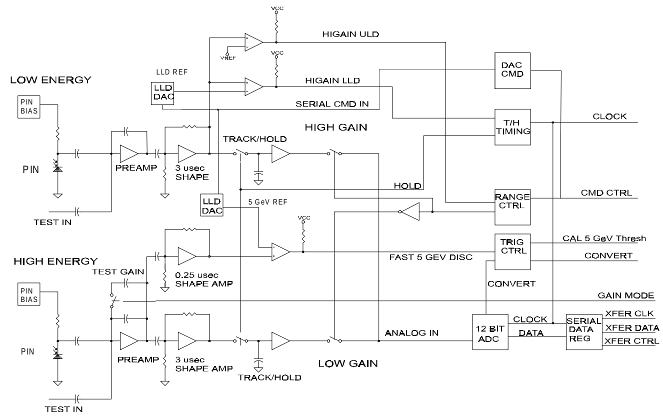

Fig. 4. Conceptual block diagram of the CsI calorimeter front end electronics.

B. *Electronics Concept*

The large number of electronics channels in the calorimeter and the large dynamic range requires the development of custom, low power front end analog application specific integrated circuits (ASICs) which provide the dual gain and high speed processing needed to meet the requirements in Table II. The front end electronics concept is shown in Fig. 4. Each end of a CsI block has two PIN diodes which support two differing gain ranges. Each signal chain consists of a preamp, shaping amp, track/hold and multiplexer to an analog to digital converter (ADC). When a GLAST event trigger is created (principally from signals in the silicon tracker), all calorimeter signal chains are digitized. Post-trigger processing compresses the calorimeter data by selecting digitized data from those CsI blocks involved with that event.

Discriminators with programmable thresholds initiate the track/hold operation and identify which gain range to digitize. A fast shaping time (~0.5 μs) signal is developed from the high energy range which can initiate a calorimeter-derived trigger of the GLAST system. The calorimeter can trigger GLAST readout for large energy depositions which do not have valid coincident tracker signals. These "calorimeter only" events utilize the imaging capability of the calorimeter to reconstruct the incident photon direction. See Lovellette et al. [3] in these proceedings for a discussion of requirements and capabilities of the GLAST data acquisition and processing system.

C. *Simulations*

The size of the CsI blocks has been chosen as a compromise between electronic channel count and position resolution within the calorimeter. The indicated size is comparable to the CsI radiation length (1.86 cm) and the Moliere radius (3.8 cm) for electromagnetic showers in CsI. The improved sampling provided by smaller (1.5 – 2 cm) block cross-sections in at least the first few layers of the

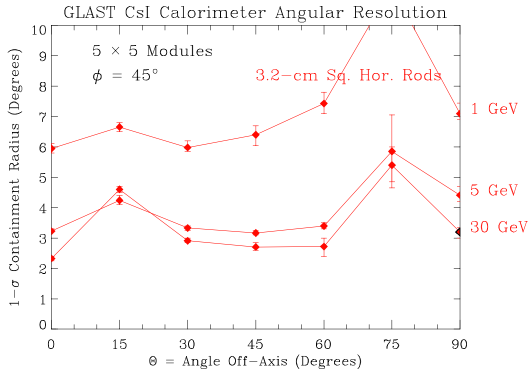

Fig. 5. Angular response (expressed as the 1σ opening angle of the angular distribution) of the calorimeter as a function of photon incident angle at three different energies.

calorimeter would provide better angular for calorimeter-only gamma-ray events. Simulations of the imaging ability of the calorimeter are being performed to further optimize this segmentation. Fig. 5 shows the results of the simulation for the baseline 3 cm × 3 cm blocks.

The simulations are also important in understanding the effects of the inactive material and gaps in the calorimeter caused by the modular design. The baseline design presents approximately 88% active CsI for vertically incident particles. The remaining 12% represent potential leakage paths. The effective gap size reduces rapidly as the incident direction departs from normal incidence.

Fig. 6 shows the simulation results for a GLAST calorimeter without gaps (solid line) and in the proposed configuration with ~ 1 cm gap at each tower boundary required by the compression cell (dashed line). The figure displays the histogram of energy deposited in the calorimeter by 5 GeV electrons incident vertically for the two cases. As

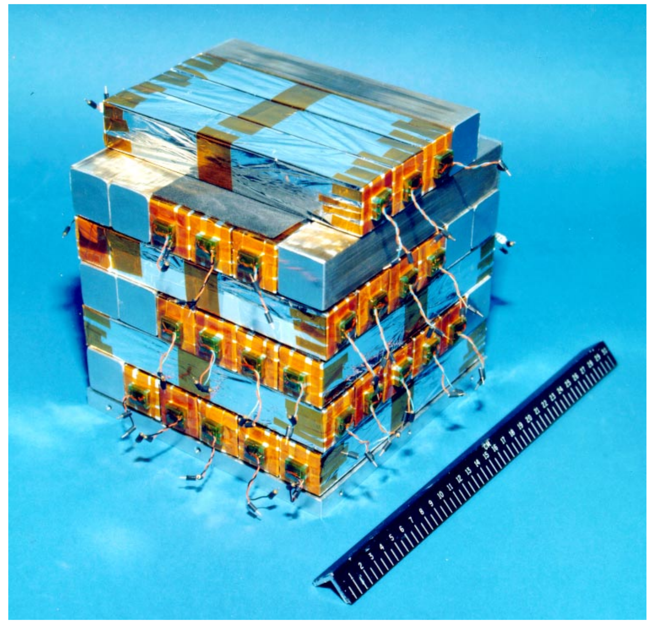

Fig. 7. Partial stack of CsI blocks for recent accelerator beam test.

seen in the figure, the gaps have negligible effects; the most notable feature being the failure to contain the entire shower in the 10 X_0 deep calorimeter (total energy deposition is always less than 5 GeV) and the low energy tailing this leakage creates.

D. Accelerator Beam Tests

We have tested a prototype CsI calorimeter consisting of 8 layers of 6 blocks (3 cm × 3 cm × 19 cm) along with a prototype silicon tracker array and plastic anticoincidence shield in an electron beam at the Stanford Linear Accelerator Center in October, 1997. Both the primary electron and

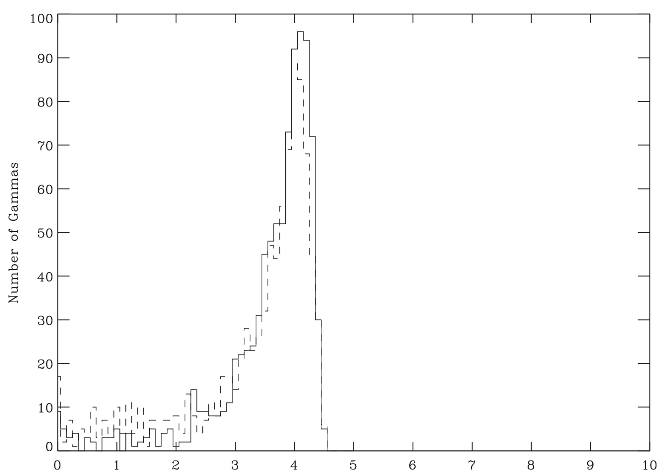

Fig. 6. Monte Carlo simulated energy response for 5 GeV electrons incident vertically. The solid curve is the response for a calorimeter without gaps; the dashed curve is the response with ~1 cm gaps caused by the GLAST modular design.

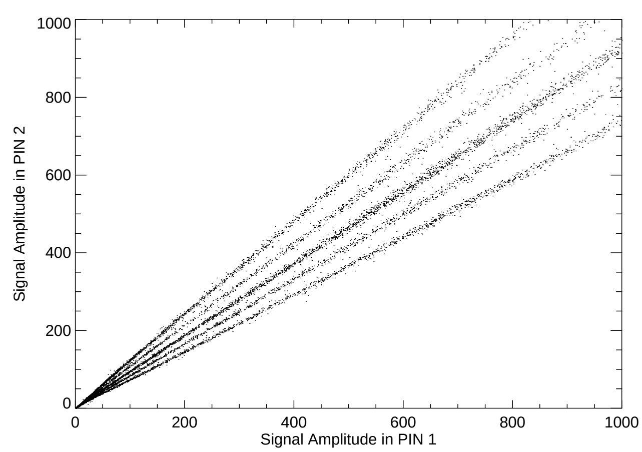

Fig. 8. Beam test data from 19 cm crystal using 5 GeV electrons. Distribution of signal amplitudes seen by the PIN diode at one end of the crystal vs that seen at the other end for 5 different positions of the beam on the crystal. Each point represents a single electron interaction.

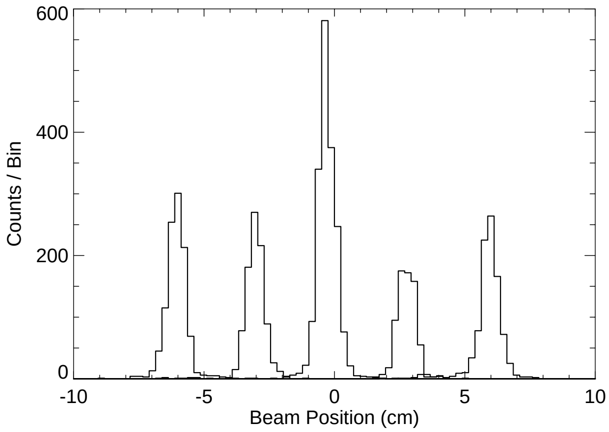

Fig. 9. Histogram of reconstructed positions for 5 GeV electrons incident at 5 positions on 19 cm CsI crystal. The widths of peaks are indicative of the beam size which is ~ 1 cm (FWHM) at this energy.

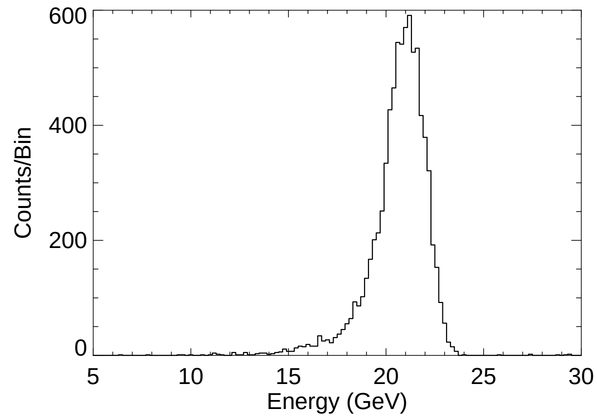

Fig. 10. Example of energy loss histogram in beam test calorimeter for 25 GeV incident electrons.

scattered photon beams in the energy range 2 – 30 GeV were used to assess the performance of these systems (see Engovatov et al. [4] in these proceedings)

For the beam test calorimeter only 32 of the 48 blocks were CsI(Tl) and the rest were brass. Fig. 7 shows a part of the stacking of the blocks. The brass blocks (ones without PIN diodes in Fig. 7) were used for mechanical support to complete the array. The beam test blocks used a single Hamamatsu S3590 PIN photodiode on each end and eV Products eV5092 hybrid preamps. The data acquisition system consisted of laboratory (NIM and CAMAC) shapers and ADCs.

One of the primary calorimeter objectives of the beam test was the study of positioning of events in a single block using the amplitude measured at each end. Fig. 8 maps the relative pulse amplitudes seen at the two ends of a 19 cm CsI block using 5 GeV electrons incident on the block at 5 different positions along its length. Each point in the plot is a single electron interaction. The five diagonal features with differing slopes clearly indicate the five incident positions in the block. The position of an event in the block is proportional to (A - B)/(A + B), where A and B are the amplitudes measured at the two ends of the log. Fig. 9 shows the histogram of events positions computed from the data of Fig. 8. The widths of the distributions are largely indicative of the electron beam spreading which is ~ 1 cm at this energy.

Fig. 10 shows the energy deposited in the calorimeter for incident electrons at 25 GeV. The calorimeter does not collect all the entire shower at these energies. The incident particle energy can be deduced by analysis of the profile of the shower energy deposition within the layers of the calorimeter.

IV. Summary

The objective of the GLAST development program is the fabrication of a prototype tower which demonstrates the readiness of the required technologies and which can be used in additional accelerator beam tests and possible balloon flight. The CsI hodoscopic calorimeter can meet the requirements of GLAST calorimetry in a straightforward manner using basic technologies that have well established space experience. The challenges are in optimizing the scientific return within the weight and power constraints for the mission. These include improvements in hodoscopic performance, careful mechanical design to minimize calorimeter leakage, and design of customized low-power electronics. Simulations will address alternate segmentation configurations. Studies of crystal surface preparation and wrapping are needed to optimize the light collection and differential light measurement for event positioning. Design work on custom ASICs for the calorimeter preamps and shaping amps is well underway at NASA's Goddard Space Flight Center.

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